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13. ABSTRACT (Maximum 200 words)

Broadband electromagnetic induction (EMI, 10's of Hz to ~ 100's of kHz) is emerging as one of the most promising technologies for discriminating subsurface unexploded ordnance (UXO) from widespread clutter. We have succeeded in performing detailed numerical simulations of EMI responses by a considerable variety of representative objects and UXO. Nonetheless, signal inversion schemes are impeded by a lack of rapid means for calculating the responses of possible target types in a great variety of depths and dispositions relative to the sensor. In this project we have developed a reduced source set (RSS) formulation of target response, which is essentially a modified and simplified method of auxiliary sources. In the RSS approach we express the same target response as would be obtained by a full-fledged, detailed, first-principles numerical solution but using only a small number of equivalent responding entities (e.g. charges, currents, surface field components, etc. We have shown that as long as the observer is at distance that is at least some significant fraction of the smallest dimension of an object of interest, the complete and the RSS responses are essentially indistinguishable.

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1. The Problem Studied

Broadband electromagnetic induction (EMI, 10's of Hz to ~ 100's of kHz) is emerging as one of the most promising technologies for discriminating subsurface unexploded ordnance (UXO) from widespread clutter. We have succeeded in performing detailed numerical simulations of EMI responses by a considerable variety of representative objects and UXO [1-6]. Still, signal inversion schemes are impeded by a lack of rapid means for calculating the responses of possible target types in a great variety of depths and dispositions relative to the sensor. Progress in the above-referenced articles has pointed the way towards a reduced source set (RSS) formulation of target response, which will be essentially a modified and simplified method of auxiliary sources (see above references). In the RSS approach one contrives to express the same target response as would be obtained by a full-fledged, detailed, first-principles numerical solution but using only a small number of equivalent responding entities (e.g. charges, currents, surface field components...). As long as the observer is at distance that is at least some significant fraction of the smallest dimension of an object of interest, the complete and the RSS responses are essentially indistinguishable. The key to application of the RSS lies in obtaining RSS solutions for each member of a set of fundamental target excitations. The fundamental excitation modes are constructed so that a simple (and readily calculated) superposition of them can describe the field actually transmitted by a real sensor. Thus the complete response (received signal) under any prospective circumstances will just be the same superposition of corresponding responses to the fundamental excitations. That is, a given linear combination of inputs corresponds to the same linear combination of outputs. The key lies in properly defining the fundamental excitation modes, parameterizing the target response to each, and determining the best way to obtain those parameters.

2. Results: Complete Solution Using the Standardized Excitations Approach (SEA)

Our approach here has been much like what has been done in radar problems for a long time, but which has not been possible heretofore for EMI. In radar work, one might determine the response of an object to a collection of unit-magnitude plane waves, each striking the object from a different angle. Any real incident beam can be constructed by some particular superposition of plane waves. The result (output, scattered field) will be the same superposition (same linear combination, same weighting) of responses to each of the constituent waves. The problem in EMI is that there are no waves. Otherwise put: There has been no immediately obvious way to express arbitrary EMI excitation fields as a sum of basic, universal, or standardized components. Our investigations have produced two ways to perform effective field decompositions in EMI realm. These are in many ways simpler than those for radar, possibly requiring fewer terms. In our initial investigations, the response of a target to each basic excitation mode was determined first from detailed numerical modeling, including all interactions, near field effects, then saved. The same kind of thing has recently been carried out based on measurements only (see papers published under this grant). That is, the response of objects to individual standard excitations has been inferred from measurements in which the primary field contained a number of these excitation components simultaneously (the normal state of affairs). Given a sufficient variety of sensor-object arrangements, one can extract the response associated with each individual excitation component. Essentially no idealization of the object or its response is required.

The first version of this approach, which we have as yet explored in the most detail, involves expressing the primary field in terms of fundamental spheroidal modes (FSM) for the standardized excitations. In particular, these are solutions in spheroidal coordinates to the Laplace equation that governs the primary (transmitted) magnetic potential field. The origin is taken to be located at the target, not the sensor, and the superposition of modes expressing the primary field is valid throughout the domain. Spheroidal modes are chosen simply because spheroidal enclosing shapes and coordinate systems conform more readily to the kinds of shapes we are interested in, therefore fewer terms will be required. The primary magnetic potential field is expressed as

$$\Psi^{PR} = \sum_{j} b_j \Psi_j = \sum_{j=\{n,m\}} b_{mn} P_m^n(\xi) P_m^n(\eta) \begin{Bmatrix} \cos m\phi \\ \sin m\phi \end{Bmatrix} \tag{1}$$

where ξ, η and the angle ϕ are just the standard "radial," "angular," and circumferential spheroidal coordinates, respectively; the subscript *j* indicates all admissible combinations of *n* and *m*; and P_m^n is the standard associated Legendre function of the first kind. These are easily calculated. The lowest modes, for each of $m = 0$ and $m = 1$, correspond just to uniform (H field) axial and transverse excitation. Higher modes provide more detail for more non-uniform excitations. For a given primary field, the key is to determine the coefficients b_j that apply when the object is in any contemplated position. This also is easily done, either by integrations that exploit the orthogonality properties of the Legendre functions, or by a simple point matching scheme.

The secondary field response Ψ_j^s to the jth standard excitation (Ψ_j) is

$$\Psi_j^s = \sum_{k} S_{j,k} \Psi_k^s \tag{2}$$

where the $S_{j,k}$ are coefficients scaling the basis Ψ_k^s. The latter can likewise consist of spheroidal Laplacian eigenfunctions

$$\Psi^s_{k=\{m,n\}} = Q_m^n(\xi) P_m^n(\eta) \begin{Bmatrix} \cos m\phi \\ \sin m\phi \end{Bmatrix} \tag{3}$$

where Q_m^n is the associated Legendre function of the second kind and, as for j, each value of k indicates different admissible combinations of m and n. In this case (spheroidal response modes) we write $S_{j,k}$ as $B_{j,k}$. Alternatively, the $S_{j,k}$ can represent hypothetical magnetic charge or current strengths, in which case each Ψ_k^s is the potential field produced by the k[th] such source. In this case we write $S_{j,k}$ as $q_{j,k}^s$, to distinguish the source based system from the spheroidal eigenfunction system for the scattered field.

We have concentrated our efforts thus far on the source-based system for the scattered field. It has the advantage that we can determine a greatly reduced source set (RSS) that produces essentially the same scattered field as a more complete, numerous set of sources, for each input FSM. Altogether, while we have pursued many variants and continue to do so, the FSM excitation system with RSS response parameters (FSM-RSS) is the approach we have formulated and tested in this project. However one parameterizes them, one can combine the relations above so that the complete secondary (scattered) field can be written as

$$\Psi^s = \sum_j b_j \Psi_j^s = \sum_j b_j \sum_k S_{j,k} \Psi_k^s \tag{4}$$

The basic ideas sketched above can be recast simply as a procedure. This produces the complete EMI response of an arbitrarily complex metallic object, including all near and far field effects, and internal interactions:

1. In any sensor-target configuration, express the primary field as a linear combination (weighted superposition) of pre-defined, fundamental, standardized excitation fields;
2. Determine the basic responses of the object, i.e. to unit magnitudes of each of these basic excitations;
3. Under any particular circumstances (e.g. sensor-object geometry), obtain the complete solution by forming a linear combination of the basic responses using the same weights b_j as produced the primary excitation. That is, a given linear combination of inputs will produce the same linear combination of corresponding outputs.

In practice, we are generally solving for the response coefficients $S_{j,k}$ here. The basic building blocks of the response, Ψ_k^s, are just defined functions attached to those coefficients, and the input spheroidal Laplacian eigensolutions are often intuitively graspable - and physically informative - field patterns. For the lowest excitation mode j = 0, the primary field is just a uniform axial H field of magnitude b_o (Figure 1). The corresponding response coefficients $S_{o,k}$ are just equivalent source magnitudes that produce the response to such a primary field. Note the next higher mode shown in the lower plot in the figure. At one end of the object the field is vectorially positive in one direction, passes through zero magnitude at the center of the object, then increases with the opposite sign. That is, at least around the axis of the target, it supplies a ~ linear variation of the primary field that can be superposed on the uniform background of the lower mode. Higher modes bring to bear more detailed and varied patterns, to accommodate any real field, especially when sinusoidal azimuthal variation is included (see (3)).

Figure 2 shows results of a test of our system against UWB EMI measurements with the Geophex GEM-3 sensor, compared to results using the next most complete approach, namely multiple offset, anisotropic dipoles. The fundamental difference between the $S_{j,k}$ we solve for here and magnetic polarizability coefficients in the commonly used single or multiple dipole models is that these $S_{j,k}$ represents the response of the *entire* target, including all internal interactions. Linked to this, the secondary field expressed through these $S_{j,k}$ are valid in near, middle, and far field. This is the reason for the accuracy of the green line in Figure 2 as opposed to that for the displaced dipoles.

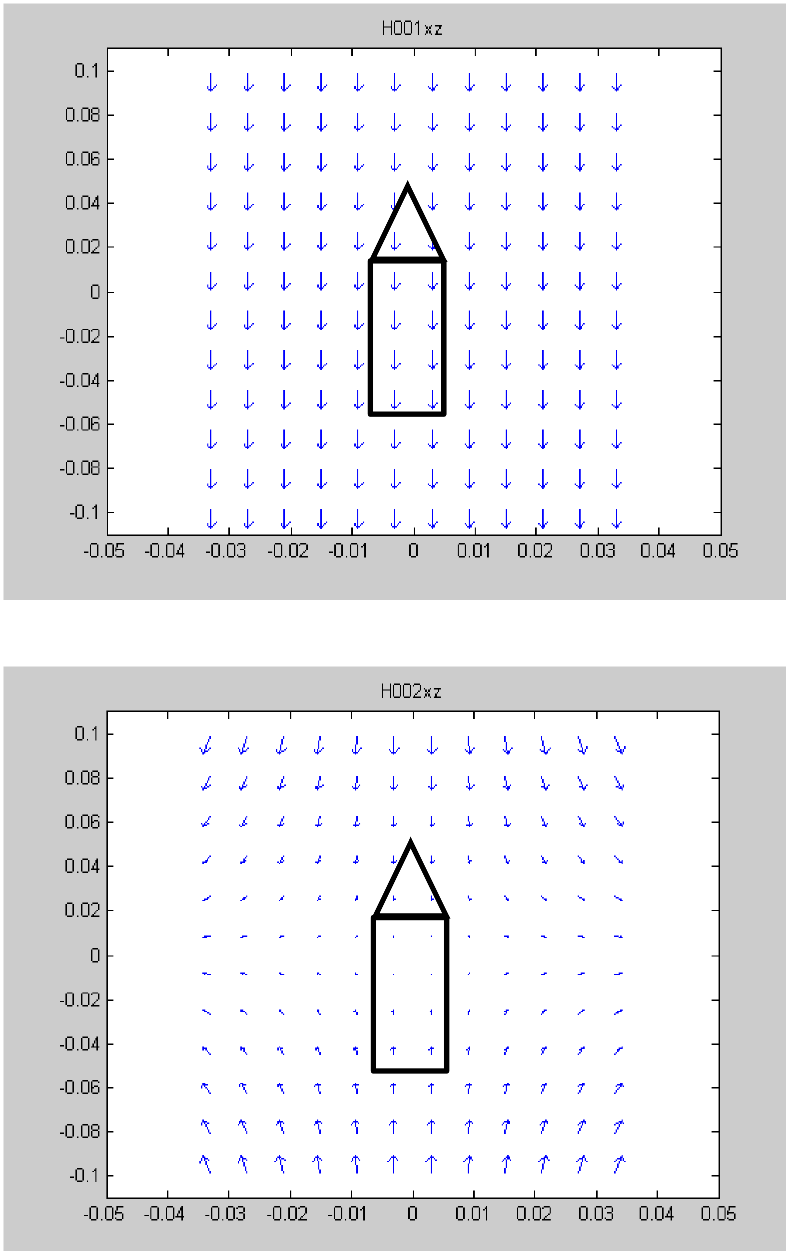

Figure 1. Transmitted magnetic field patterns corresponding to two of the lowest excitation modes, around a hypothetical target shape. Edge labels correspond to space coordinates (arb) on two sides of a plane through the target axis.

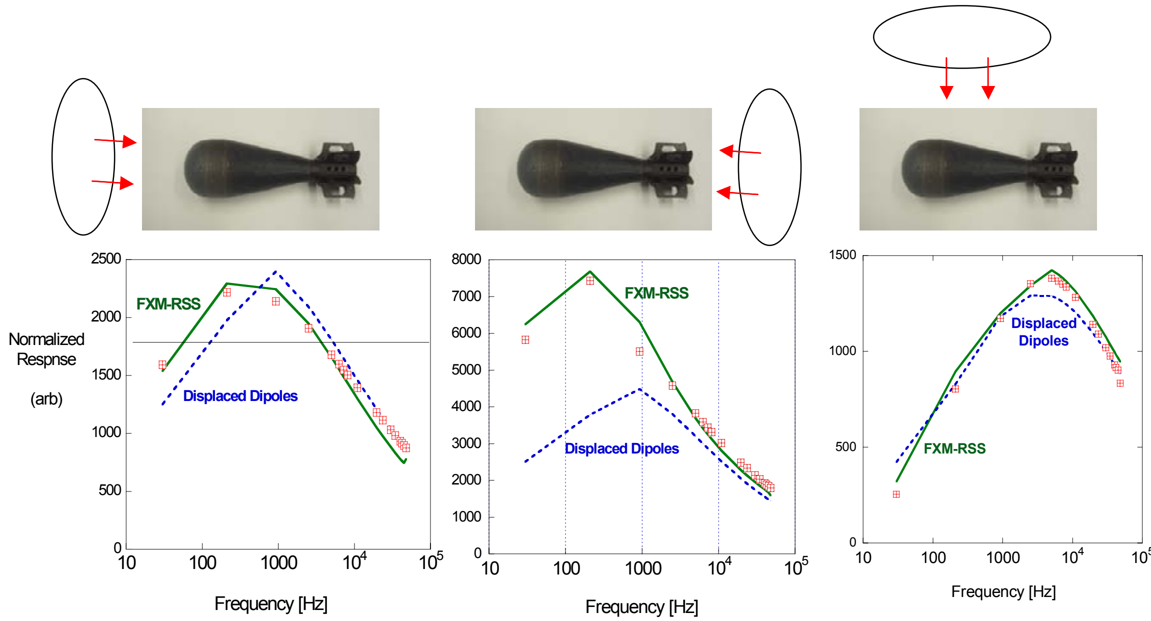

Figure 2. GEM-3 measurements (markers) compared to two modeling approaches.

This is written as if assuming a monostatic, frequency domain system. The generalization to a bistatic and/or time domain system is straightforward. In the latter case, with step function (in time) input, equation (1) would refer to the initial condition and the stored modal responses would cover the entire time period of interest.

Details of the results in this project appear in a number of publications listed in Section 4 below. These include treatment of the definition of the fundamental spheroidal excitations; computation and processing for their coefficients; ill-conditioning issues surrounding that computation and various treatments thereof; testing against other modeling approaches and measurements; implementation in inversion schemes including Bayesian, weighted least squares, and pattern matching classification variants.

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4. Publications

4.1 Journals:

K. Sun, K O'Neill, I. Shamatava, F. Shubitidze, K. D. Paulsen (2003). A fast forward model for simulating EMI scattering with realistic sensors and elongated objects, ACES J., vol 18, no 4, p 97-106.

K. Sun, K. O'Neill, F. Shubitidze, I. Shamatava, and K.D. Paulsen (2004). Fundamental spheroidal excitation modes for fast inversion of EMI survey data, to be submitted, June 2004.

F. Shubitidze, K. O'Neill, K. Sun, I. Shamatava, and K.D. Paulsen (2004). Source-based fundamental excitation and response modes for inversion and classification of buried metallic objects, to be submitted July 2004.

4.2 Conferences (full paper published):

K. Sun, K O'Neill, I. Shamatava, F. Shubitidze (2003). Application of prolate spheroid solutions in simulation of EMI scattering with realistic sensors and objects, Proc. Appl. Comput. EM Symp (ACES), 2003, Monterey CA, 24-28 Mar 2003, p.531-537.

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K. Sun, K O'Neill, F. Shubitidze, I. Shamatava, K. D. Paulsen (2004). Fast data-derived fundamental spheroidal excitation models with application to UXO identification, SPIE Defense & Security Symp., 12-16 April 2004, Orlando, FL.

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